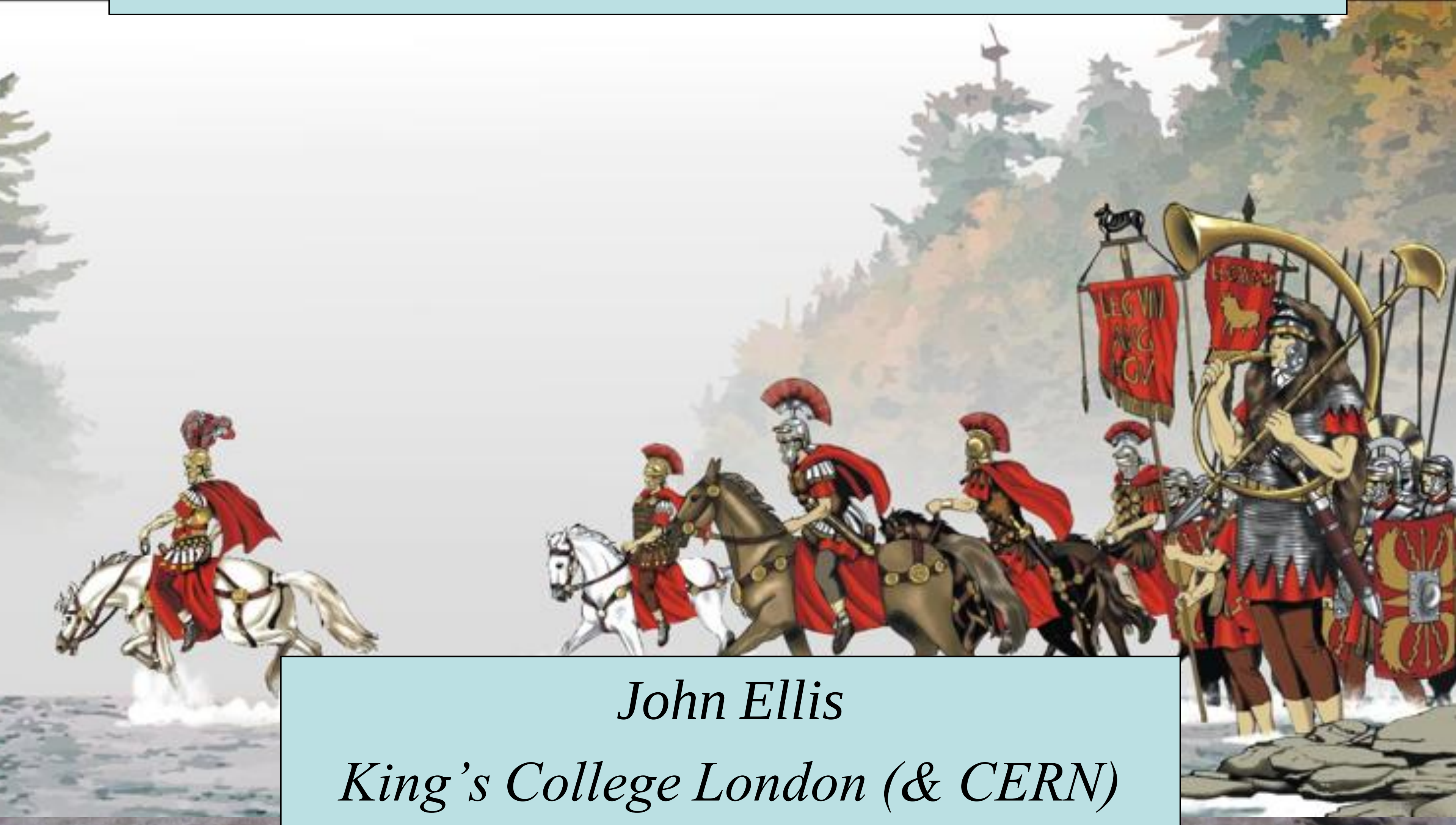
Crossing the Scalar Rubicon: Once or Twice?



John Ellis

King’s College London (& CERN)

Completing the Holy Trinity

- Scale hierarchy possible only in theory that can be calculated over many magnitudes of energy

Renormalizable

- Theorem: (1) vectors (2) fermions (3) scalars
- Need to specify:

Cornwall, Levin & Tiktopoulos; Bell; Llewellyn-Smith

(1) group (2) representations (3) symmetry breaking

(1) = SU(3) × SU(2) × U(1) [so far]

(2) = Singlets + doublets + triplets

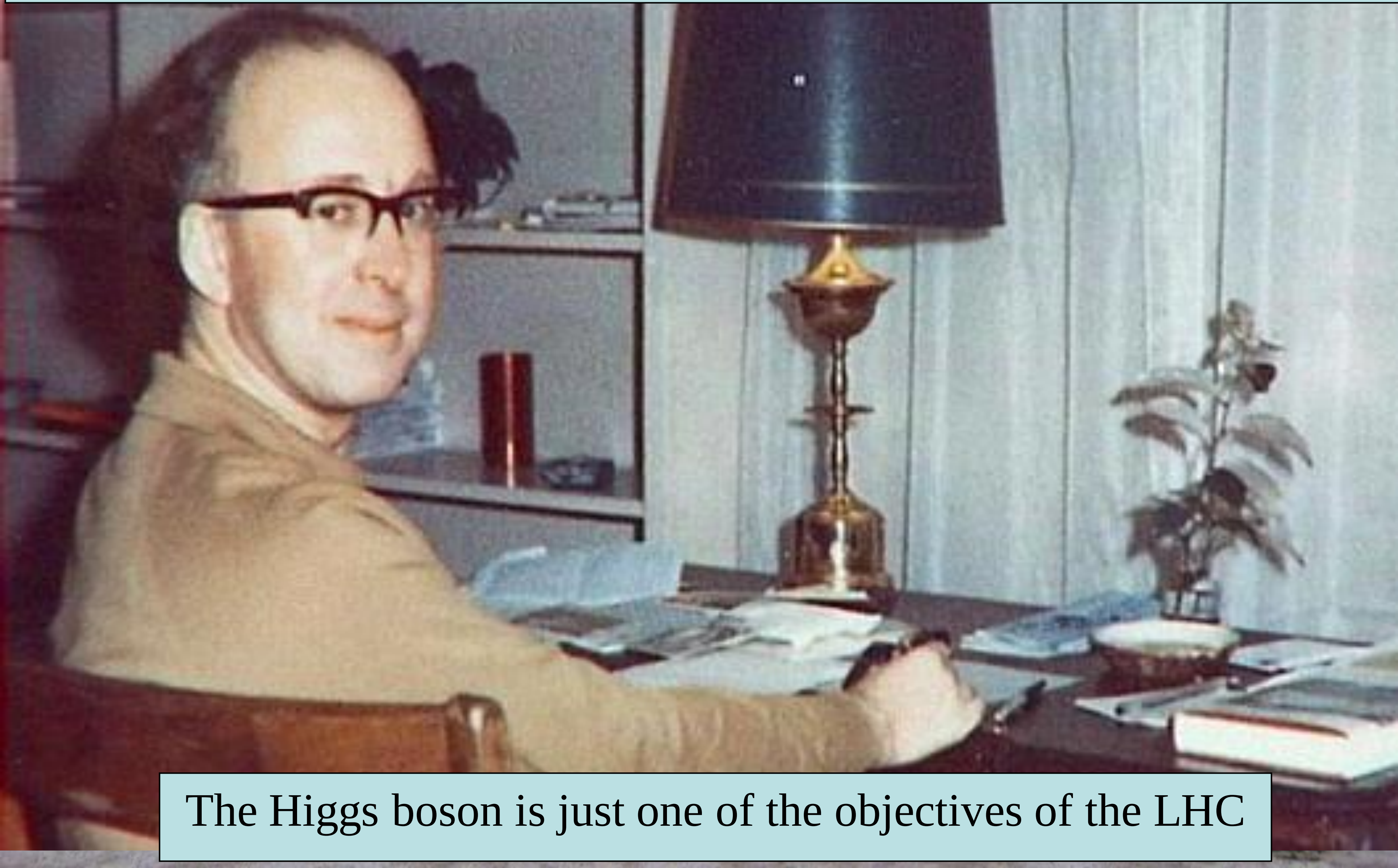
- Finally:

(3) A scalar, mechanism of symmetry breaking

Scalars Come of Age

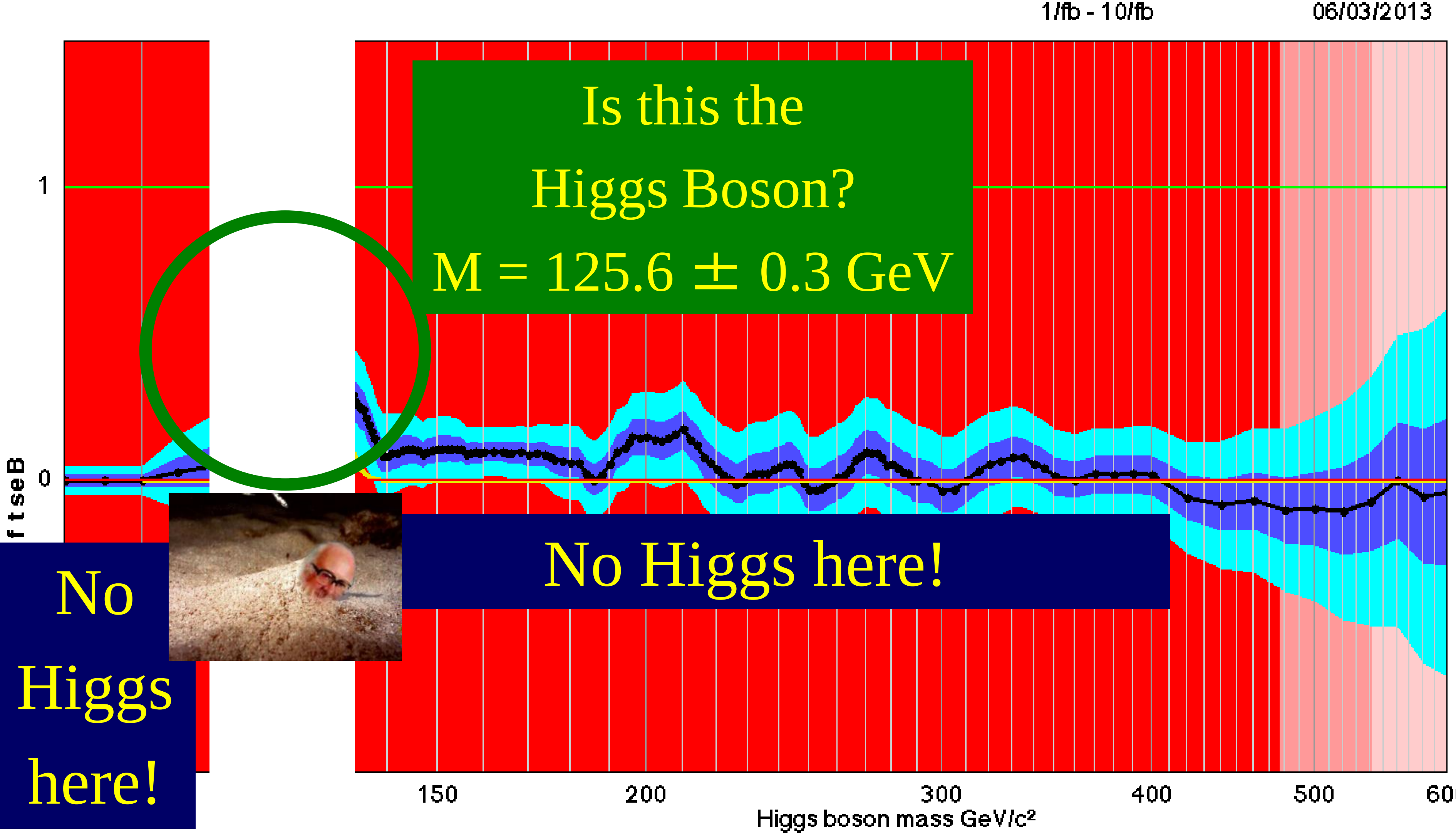
- A new boson discovered at the LHC
  - A scalar, beyond any reasonable doubt
  - Consistent with the Higgs of the Standard Model
- Circumstantial evidence for scalar inflaton
  - $\Omega \sim 1$, tilt in spectrum of scalar perturbations, …
  - No sign of non-Gaussianity, strings, defects, …
- Data compatible with Starobinsky ($R + R^2$) model
- Similar predictions in Higgs inflation: **BUT** M_H?
- Also consistent with simplest Wess-Zumino model
- No-scale supergravity with WZ = Starobinsky!

The Quest for the Higgs Boson

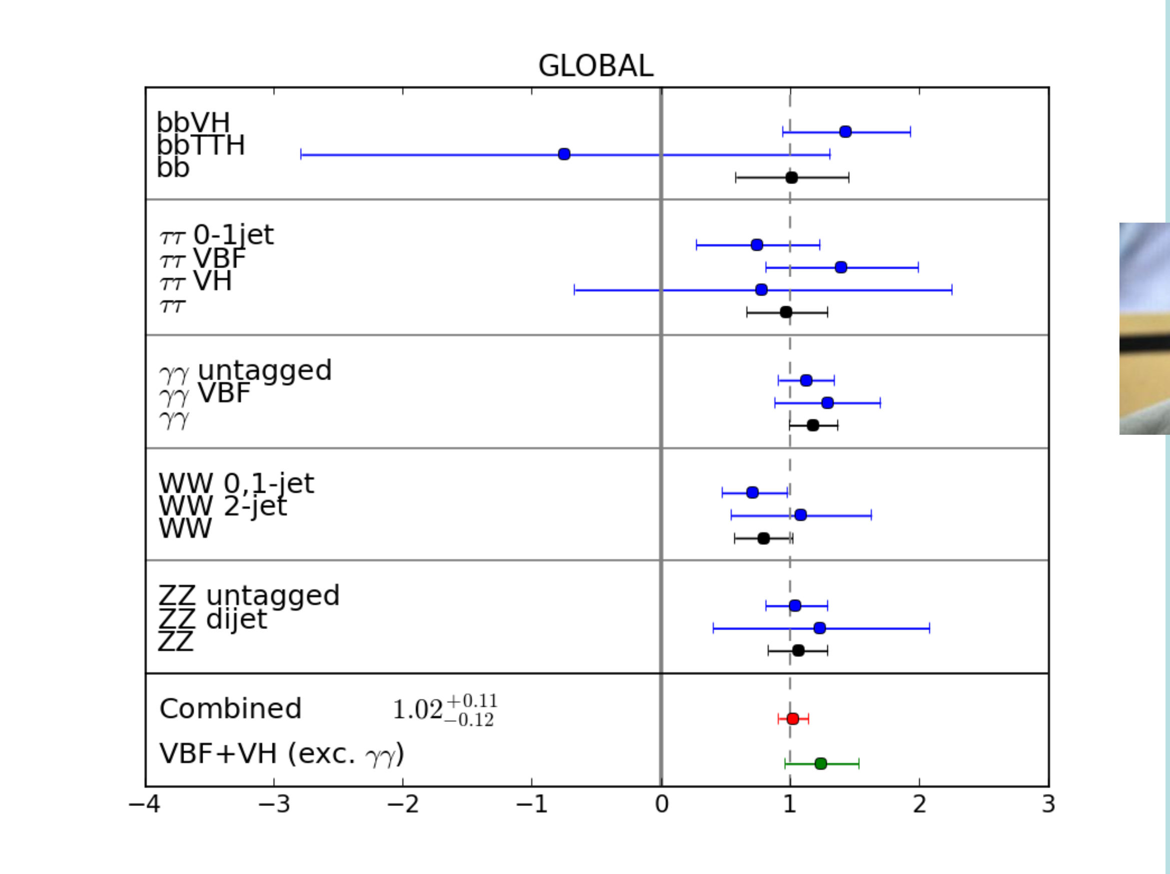


The Higgs boson is just one of the objectives of the LHC

Unofficial Combination of Higgs Search Data from March 6th



Couples like Higgs of Standard Model



- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

The Particle Higgsaw Puzzle

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

What is it ?

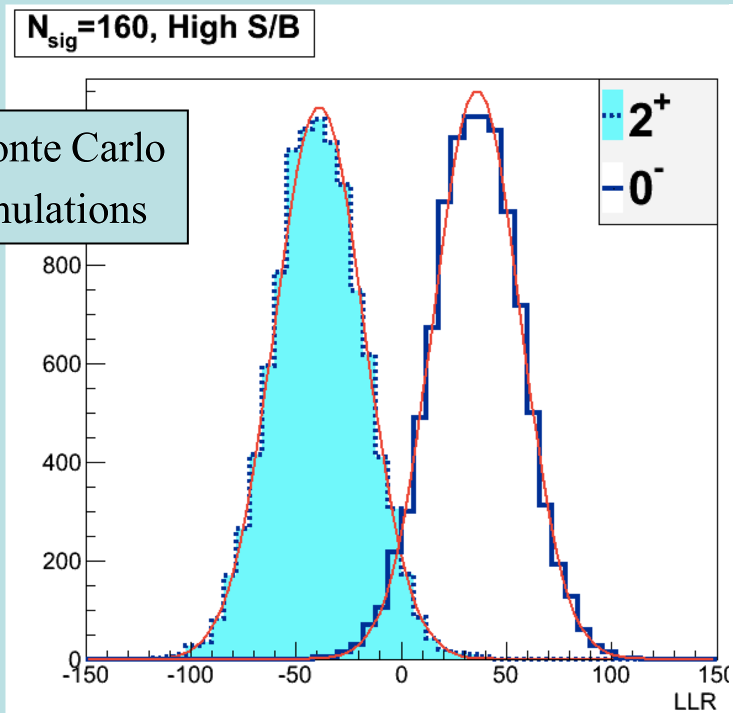
- Does it have spin 0 or 2?
- Is it scalar or pseudoscalar?
- Is it elementary or composite?
- Does it couple to particle masses?
- Quantum (loop) corrections?
- What are its self-couplings?

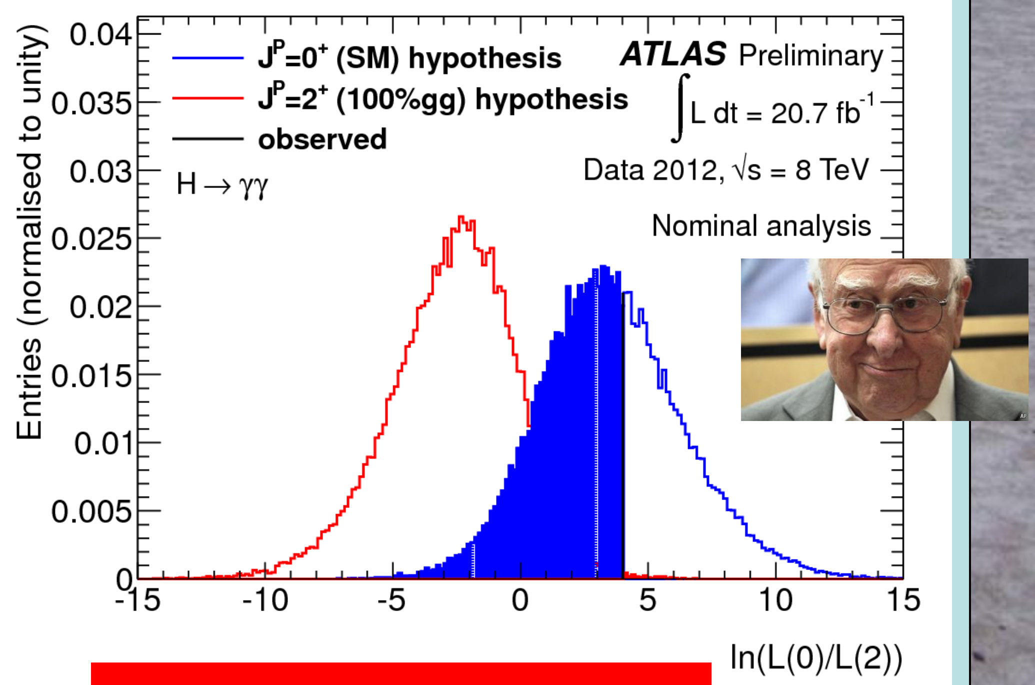
Does the ‘Higgs’ have Spin Two ?

- Discriminate spin 2 vs spin 0 via angular distribution of decays into $\gamma\gamma$

JE & Hwang: arXiv:1202.6660

Monte Carlo simulations

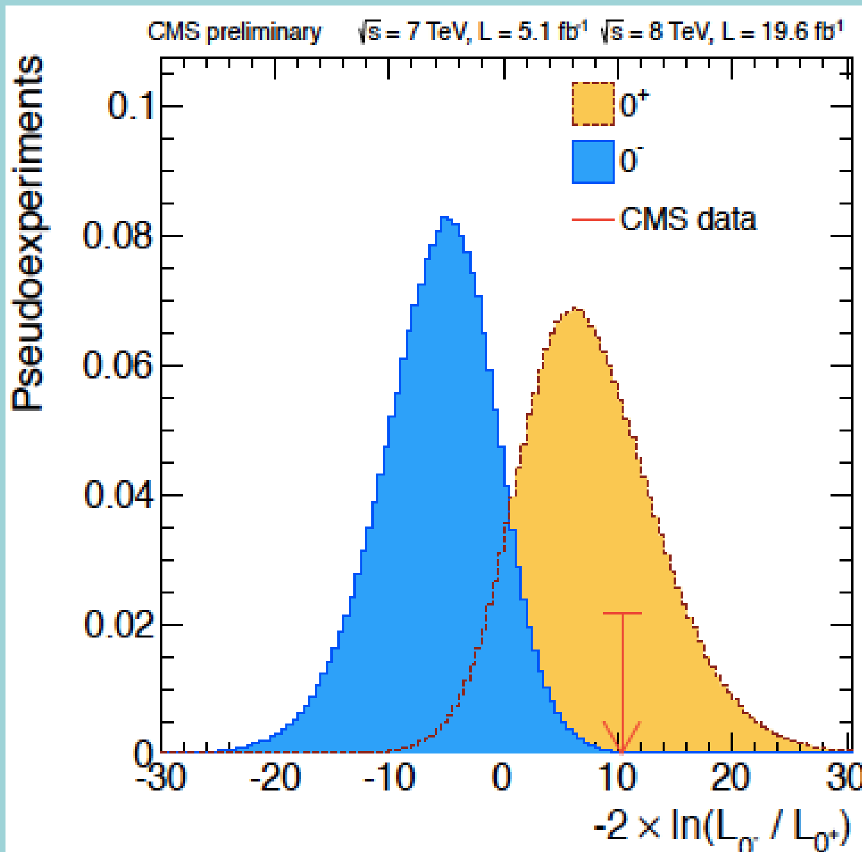


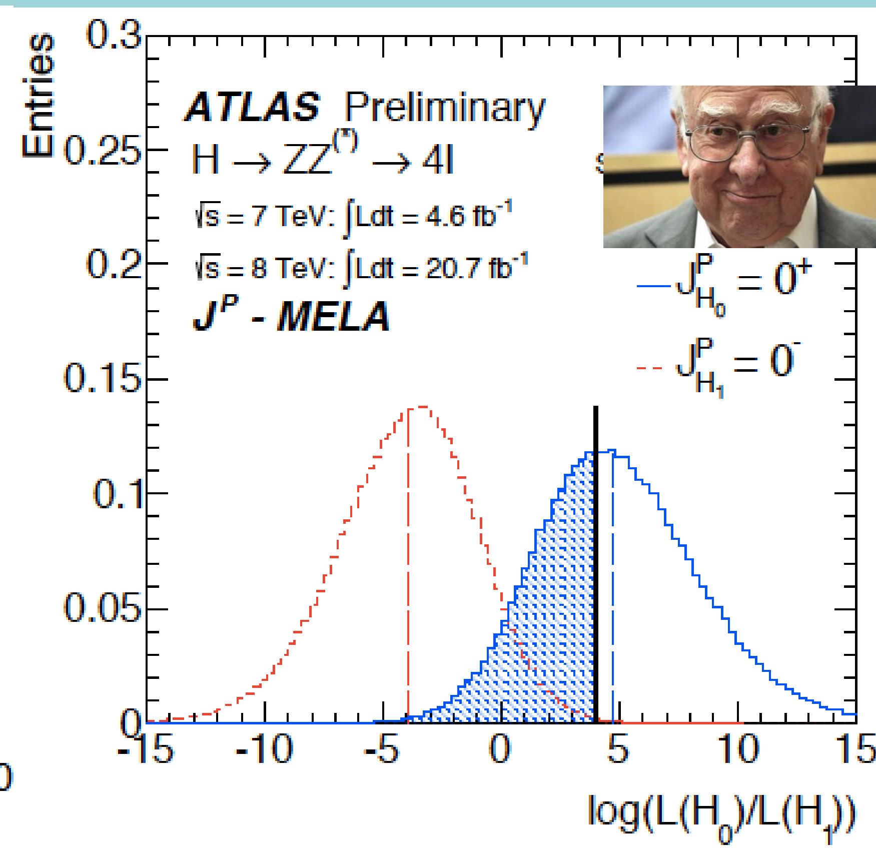


JE, Fok, Hwang, Sanz & You: arXiv:1210.5229

2^+ disfavoured @ 99%

The 'Higgs' is probably a scalar



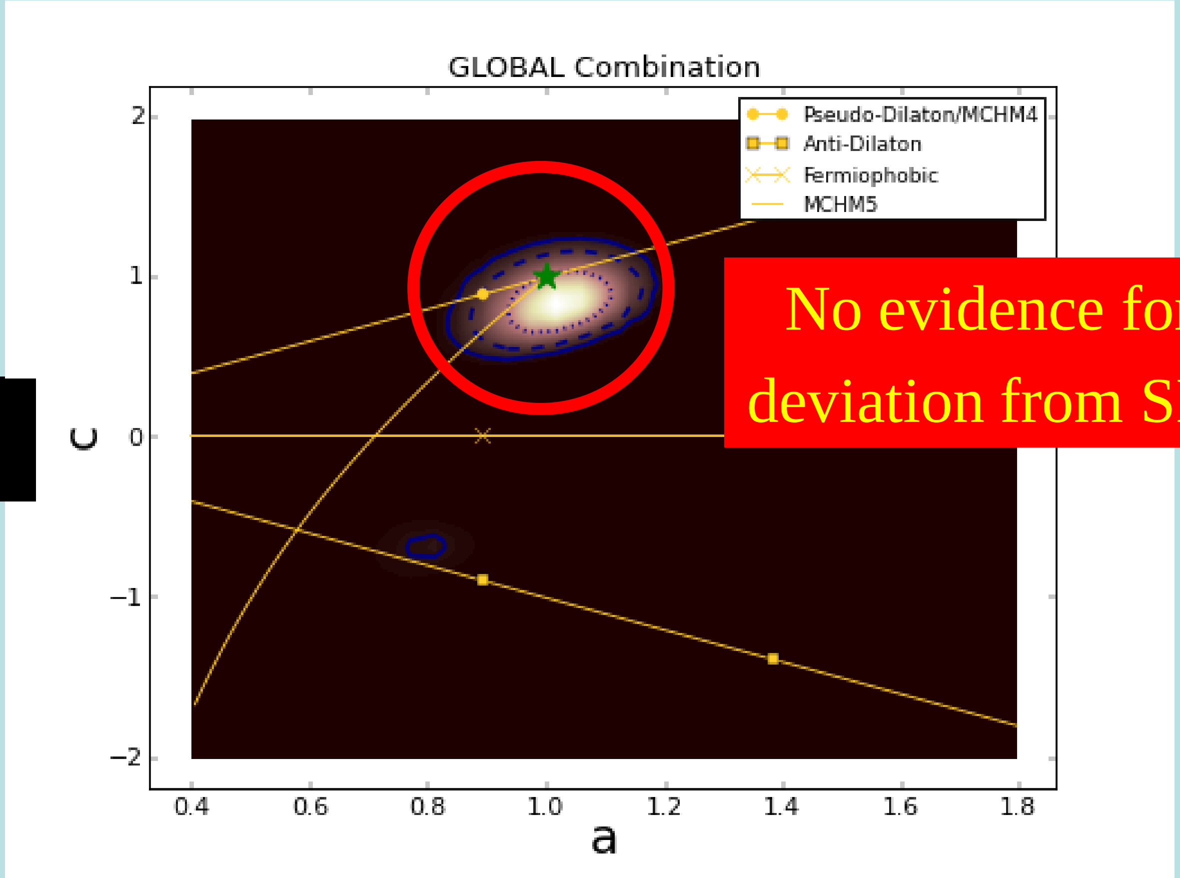


- Pseudoscalar 0^- disfavoured at > 99% CL

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

Global



No evidence for deviation from SM

- Standard Model: $a = c = 1$

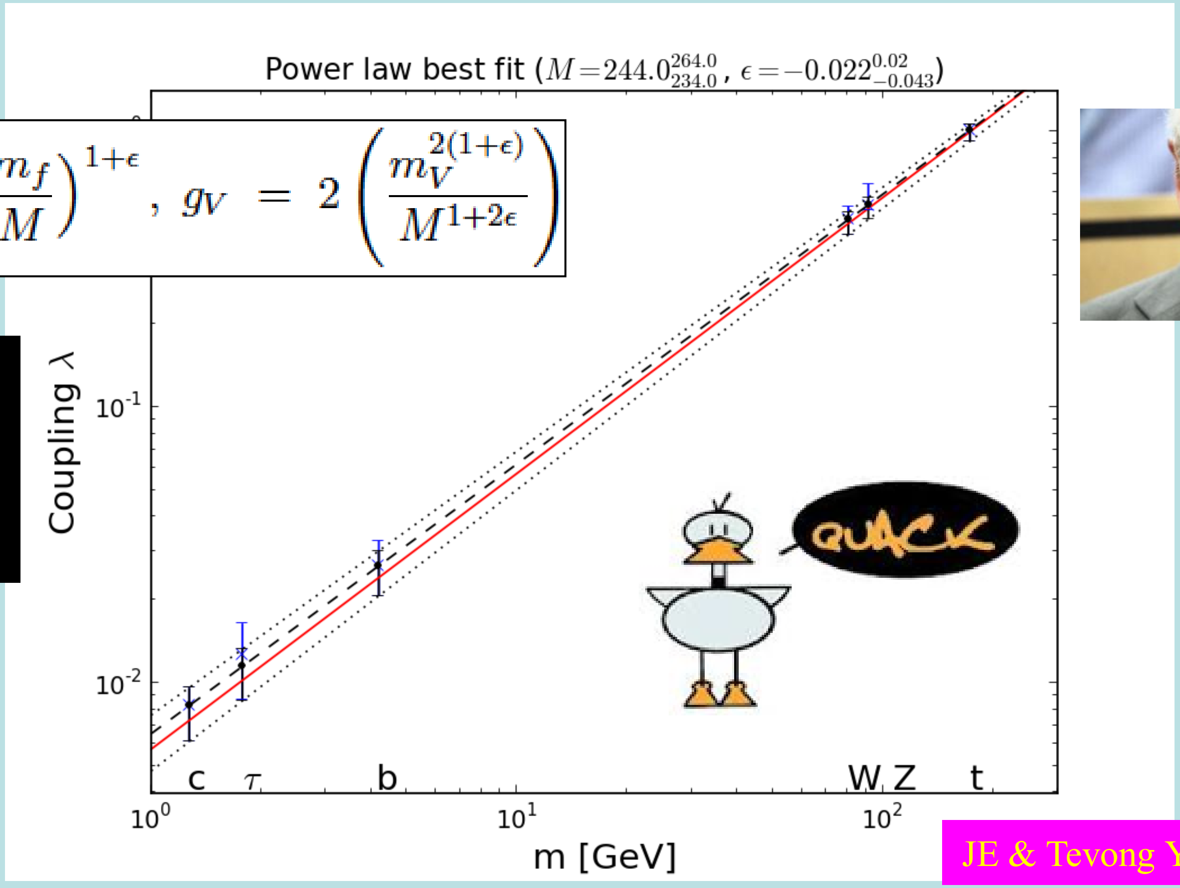
JE & Tevong You, arXiv:1303.3879

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Global fit

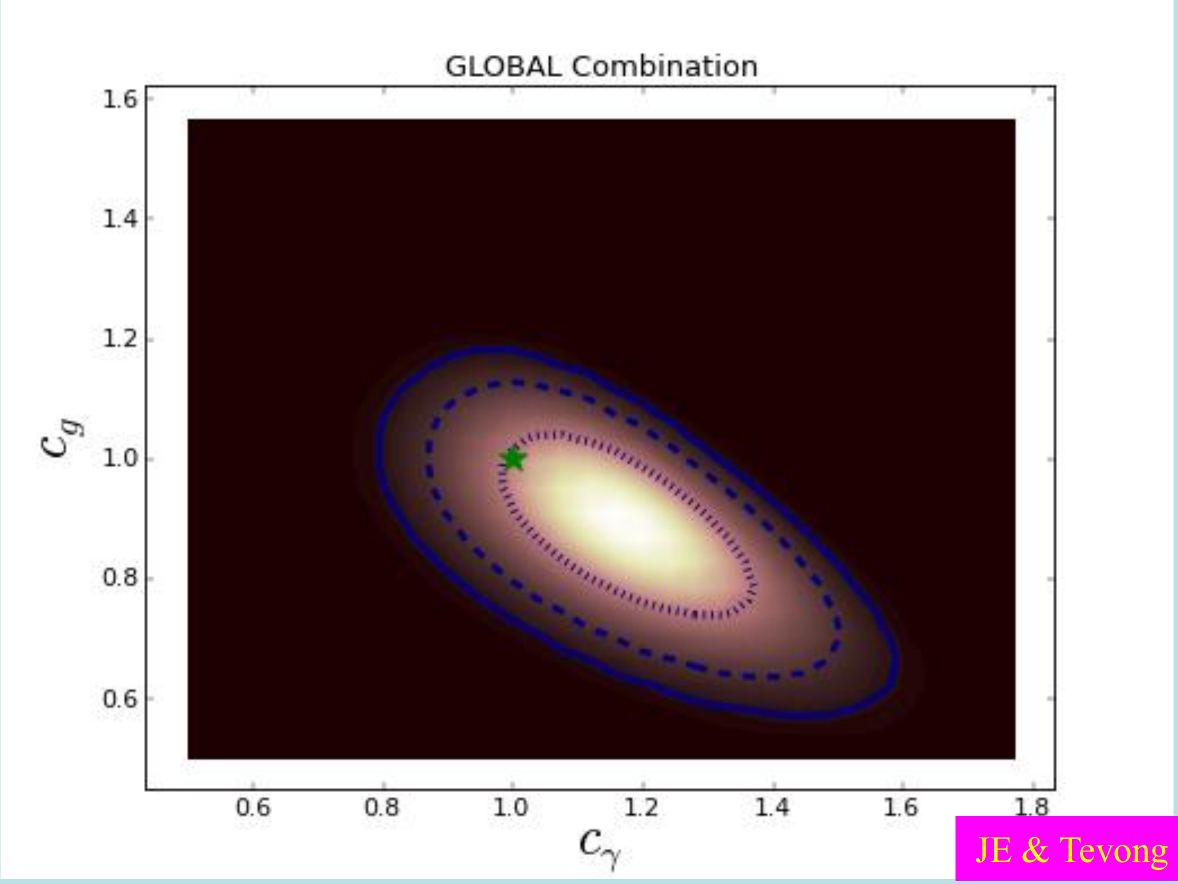


JE & Tevong You, arXiv:1303.3879

- **Red line = SM**, dashed line = best fit

Loop Corrections ?

- ATLAS sees excess in γγ, CMS sees deficit



JE & Tevong You, arXiv:1303.3879

- Loop diagrams ~ Standard Model?

Beyond any Reasonable Doubt

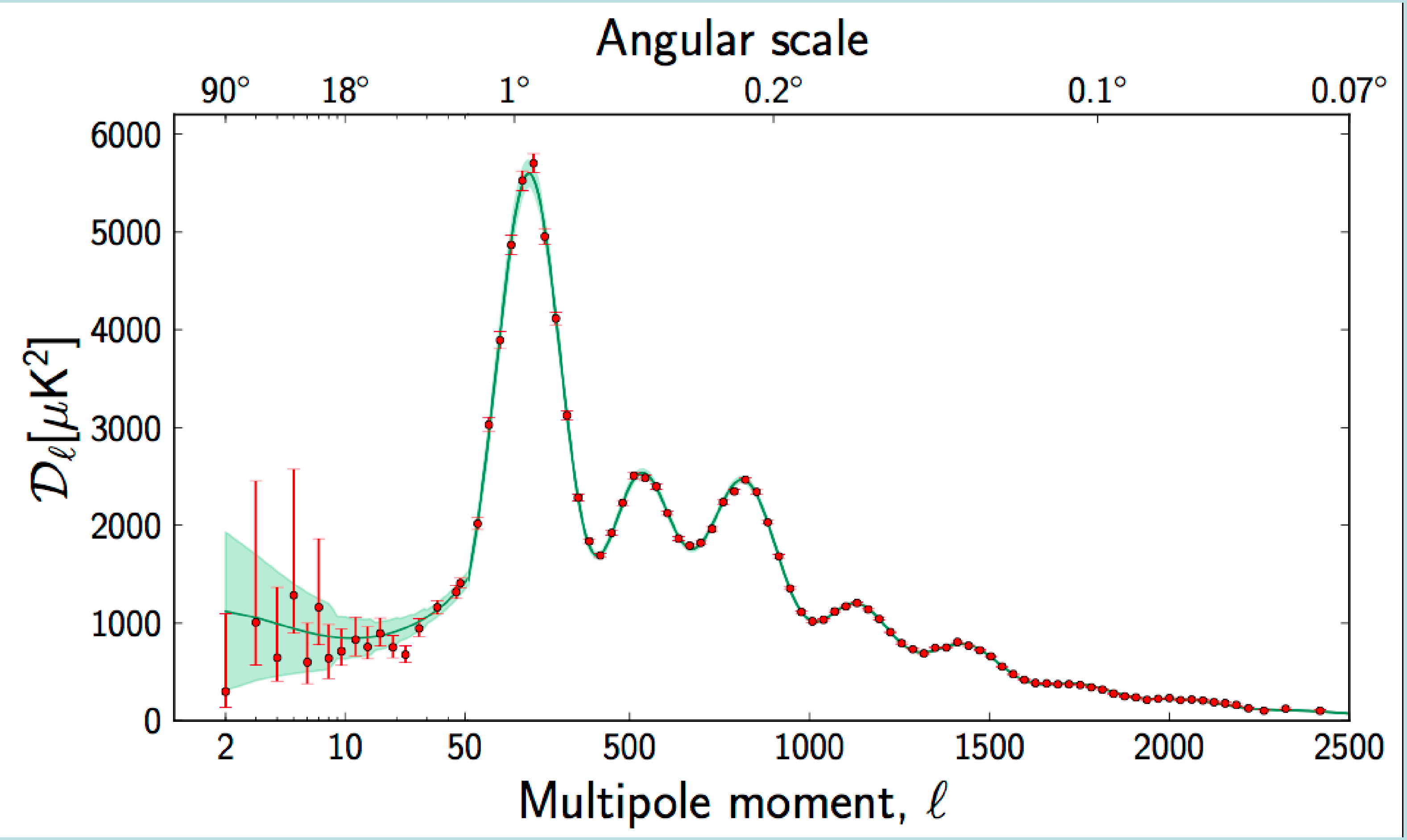
- Does it have spin 0 or 2?
  - **Simple spin 2 couplings excluded**
- Is it scalar or pseudoscalar?
  - **Pseudoscalar strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**
- Quantum (loop) corrections?
  - **$\gamma\gamma$ coupling > Standard Model?**
- What are its self-couplings? **Hi-lumi LHC or …?**

What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values

Cosmological Inflation in Light of Planck



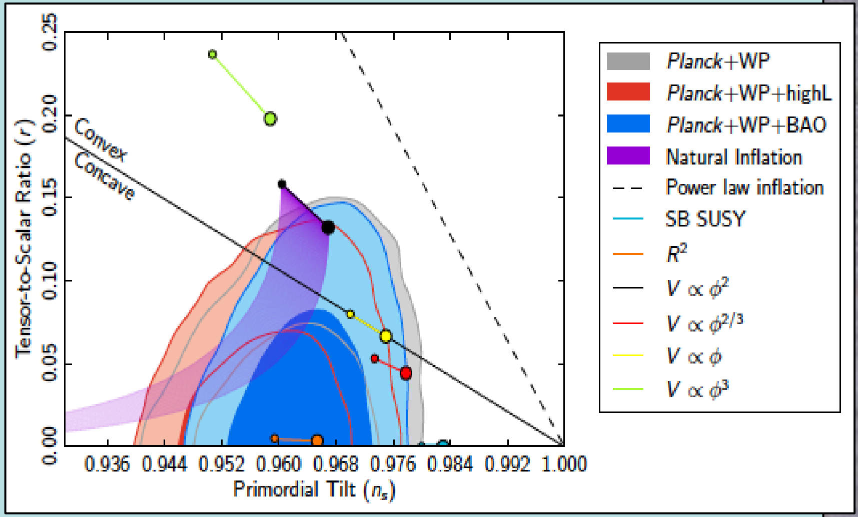
- **A scalar in the sky? Higgs? Supersymmetry?**

Inflationary Models in Light of Planck

- Planck CMB observations consistent with inflation
- Tilted scalar perturbation spectrum:

$$n_s = 0.9603 \pm 0.073$$

- BUT strengthen upper limit on tensor perturbations: $r < 0.10$
- Challenge for monomial inflationary models
- **Starobinsky R^2? Higgs?**
- **Wess-Zumino to rescue?**



Croon, JE & Mavromatos: arXiv:1303.6253

Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\,(R + R^2/6M^2)$$

Starobinsky, 1980

- **No scalar!?**
- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x\left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

- Conformally equivalent to scalar field model:

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2\left(1 - e^{-\sqrt{2/3}\varphi'}\right)^2\right]$$

Whitt, 1984

Higgs Inflation: a Single Scalar?

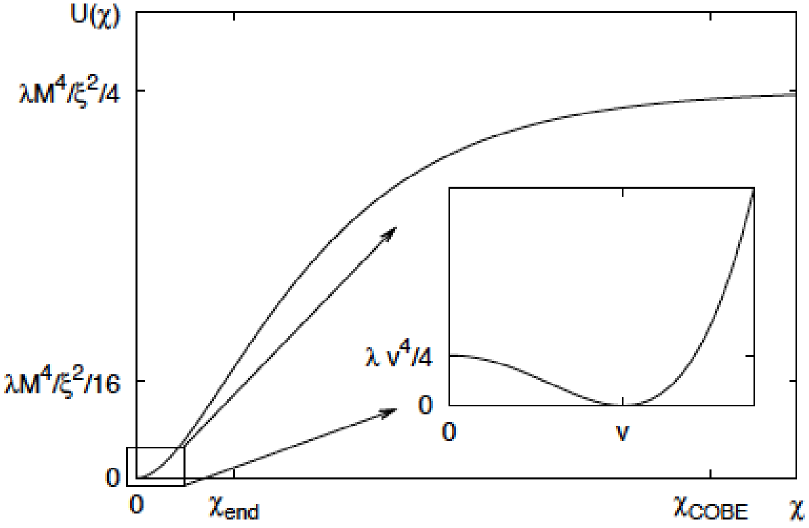
Bezrukov & Shaposhnikov, arXiv:0710.3755

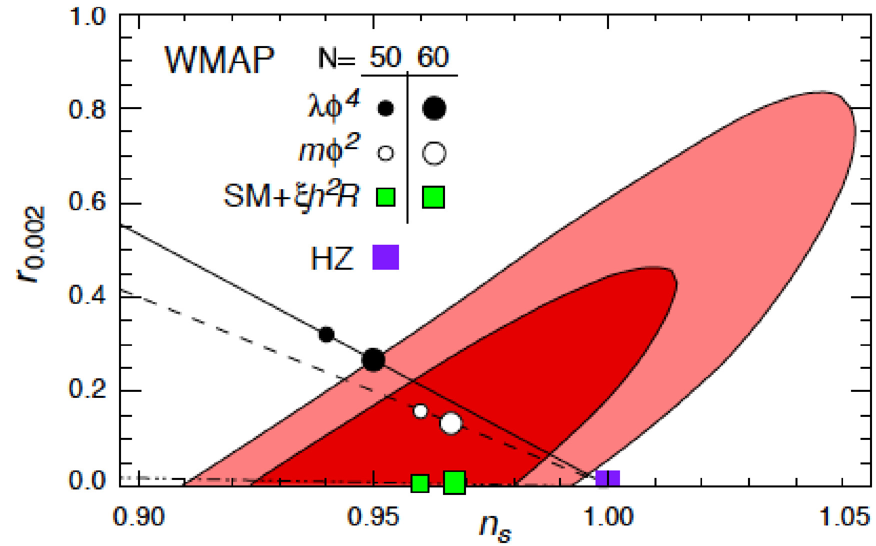
- Standard Model with non-minimal coupling to gravity: $$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M^2+\xi h^2}{2}R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2-v^2\right)^2\right\}$$
- Consider case $1 \ll \sqrt{\xi} \lll 10^{17}$: in Einstein frame $$S_E = \int d^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi)\right\}$$
- With potential: $$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$ Similar to Starobinsky, but not identical
- Successful inflationary potential at $\chi \gg M_P$

Higgs Inflation: a Single Scalar?

- Successful inflation for

$$\xi \simeq \sqrt{\frac{\lambda}{3}}\frac{N_{\rm COBE}}{0.027^2} \simeq 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2}v}$$





- **BUT:**

Bezrukov & Shaposhnikov, arXiv:0710.3755

  – Need to take into account ≥ 2-loop corrections

  – Requires λ > 0 beyond M_P: need M_H > 127 GeV?

  – Question of naturalness

Higgs Inflation vs the LHC

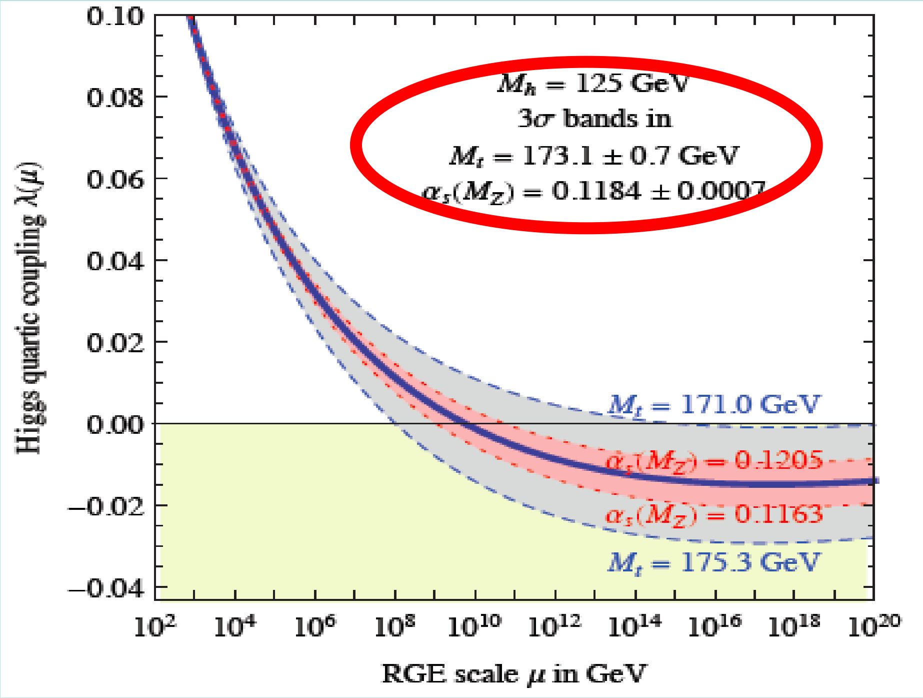
- Effective Higgs potential quartic parameter λ:

  λ > 0 at low scale

- Higgs inflation needs

  λ > 0 beyond M_P

- BUT: renormalization by t quark drives λ < 0 at some scale Λ



- λ probably < 0 @ M_P → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Effective Potential in Single-Field Model

- Consider single real field with double-well potential: $V = A\phi^2(v-\phi)^2$
- Shallower than φ^2 for

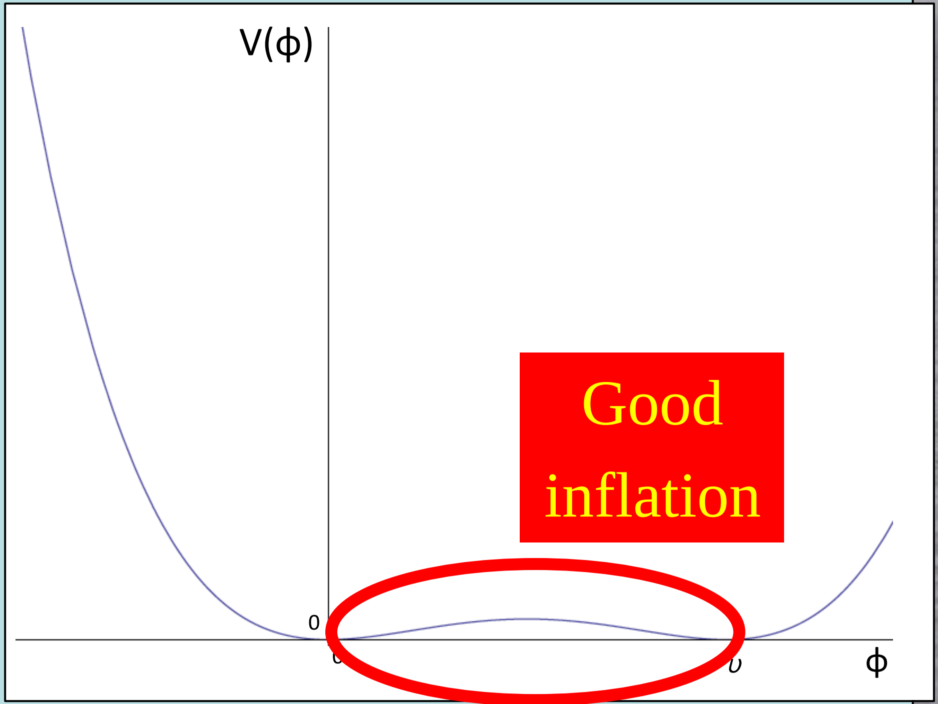
  $0 < \varphi < v$

- Better tensor-to-scalar

  ratio r for $0 < \varphi < v$

- Steeper than φ^2 for

  $\varphi < 0$ or $> v$: worse r



Croon, JE & Mavromatos: arXiv:1303.6253

Inflation Cries out for Supersymmetry

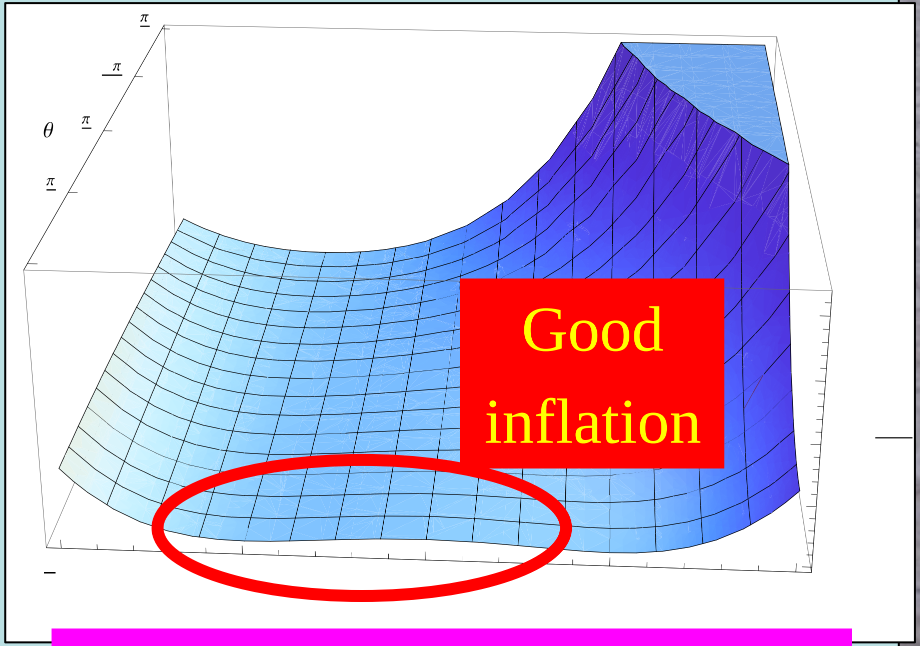
- Want “elementary” scalar field
  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations
- Prefer mass << M_P
  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling λ << 1
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive, & Tamvakis: 1983

Effective Potential in Wess-Zumino Model

$$W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

- Effective potential: $V = \left|\frac{\partial W}{\partial \phi}\right|^2 = Av^4(x^4 - 2\cos\theta x^3 + x^2)$
- Equivalent to single-field model for θ = 0 (good)
- Combination of $\varphi^2 + \varphi^4$ for $\theta = \pi/2$ (no good)
- **Good inflation for suitable μ, λ**



Croon, JE & Mavromatos: arXiv:1303.6253

Wess-Zumino Inflation in Light of Planck

- Consistent with Planck for x_i = 0.3, 0.4

Value of x_i	0.1	0.2	0.3	0.4
Derived quantity				
$\frac{v^2}{M_{Pl}^2}$	18000	4200	1600	710
ϵ	0.0085	0.0067	0.0045	0.0020
η	0.0062	0.00074	-0.0073	-0.022
ξ	-0.000053	-0.000077	-0.000079	-0.000050
r	0.14	0.11	0.072	0.031
n_s	0.961	0.961	0.958	0.945
α_s	-1.4×10^{-6}	-1.3×10^{-6}	-1.4×10^{-6}	-1.1×10^{-6}
λ	4.3×10^{-8}	1.0×10^{-7}	2.1×10^{-7}	4.1×10^{-7}

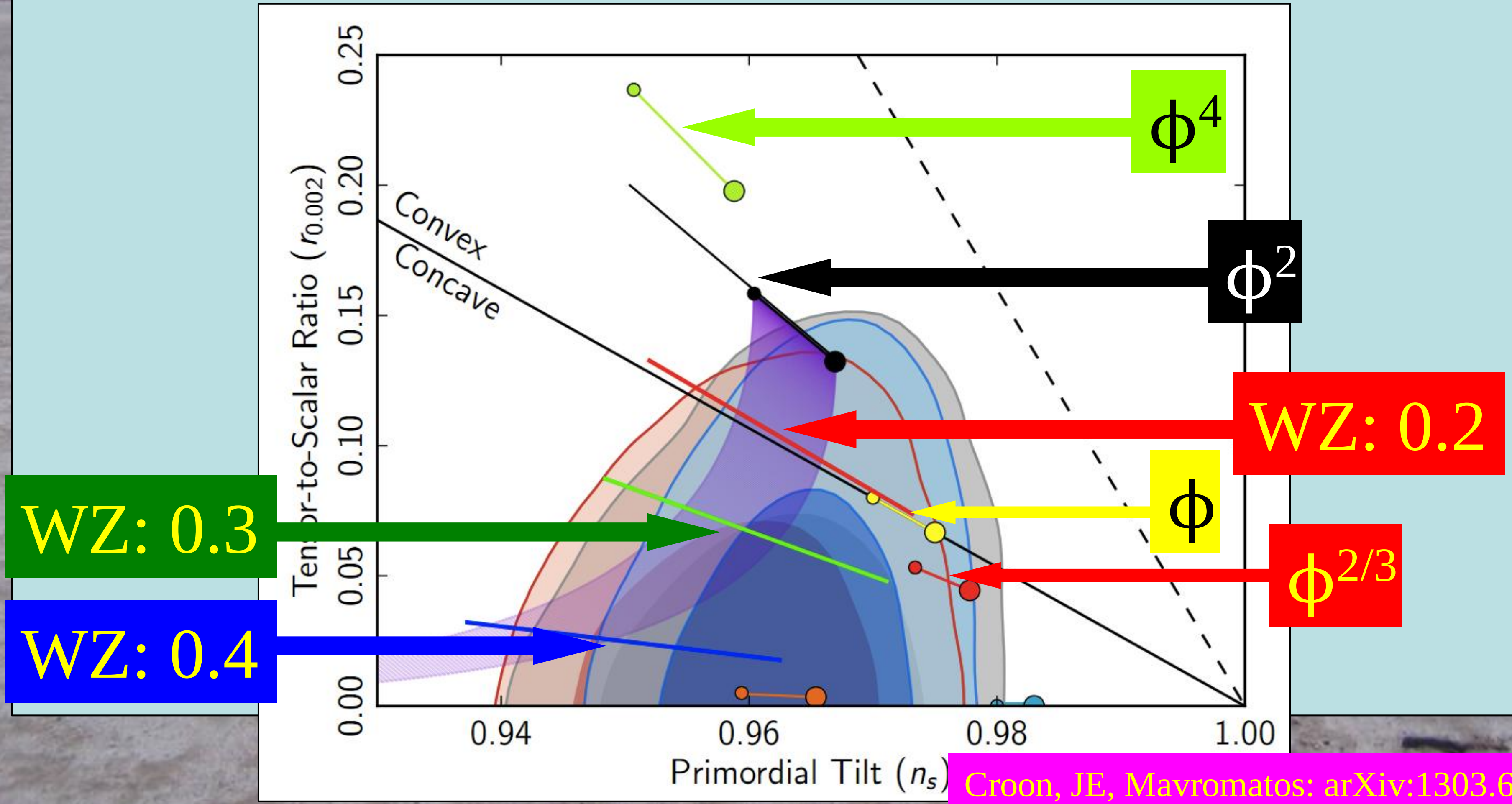
- Numbers calculated for N = 50 e-folds

Good inflation

Croon, JE & Mavromatos: arXiv:1303.6253

Wess-Zumino Inflation in Light of Planck

- Consistent with Planck for x_i = 0.2, 0.3, 0.4



Croon, JE, Mavromatos: arXiv:1303.6253

No-Scale Supergravity Inflation

- The only good symmetry is a local symmetry
- Early Universe cosmology needs gravity
- **Supergravity**
- **BUT**: potentials in generic supergravity models have potential 'holes' with depths $\sim - M_P^4$
- **Exception**: no-scale supergravity
  - Appears in compactifications of string
  - Flat directions, scalar potential ~ global model + controlled corrections

No-Scale Supergravity Inflation

- Simplest SU(2,1)/U(1) example:
- Kähler potential: $K = -3\ln(T + T^* - |\phi|^2/3)$
- Superpotential: $W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$
- Assume modulus *T = c/2* fixed by 'string dynamics'
- Ef $\mathcal{L}_{eff} = \frac{c}{(c-|\phi|^2/3)^2}|\partial_\mu\phi|^2 - \frac{\hat{V}}{(c-|\phi|^2/3)^2}$: $\hat{V} \equiv \left|\frac{\partial W}{\partial \phi}\right|^2$
- Modifications to globally supersymmetric case
- Good inflation possible …

JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Supergravity Inflation

- In terms of canonical field χ: $\phi = \sqrt{3c}\tanh\left(\frac{\chi}{\sqrt{3}}\right)$

$$\mathcal{L}_{eff} = \mathrm{sech}^2((\chi - \chi^*)/\sqrt{3})\left[|\partial_\mu \chi|^2 - \right.$$
$$\left.(\frac{3}{c})\left|\sinh(\chi/\sqrt{3})\left(\hat{\mu}\cosh(\chi/\sqrt{3}) - \sqrt{3c}\lambda\sinh(\chi/\sqrt{3})\right)\right|^2\right]$$

- Define $\chi = (x + iy)/\sqrt{2}$, $\hat{\mu} = \mu\sqrt{c/3}$, choose $\lambda = \mu/3$

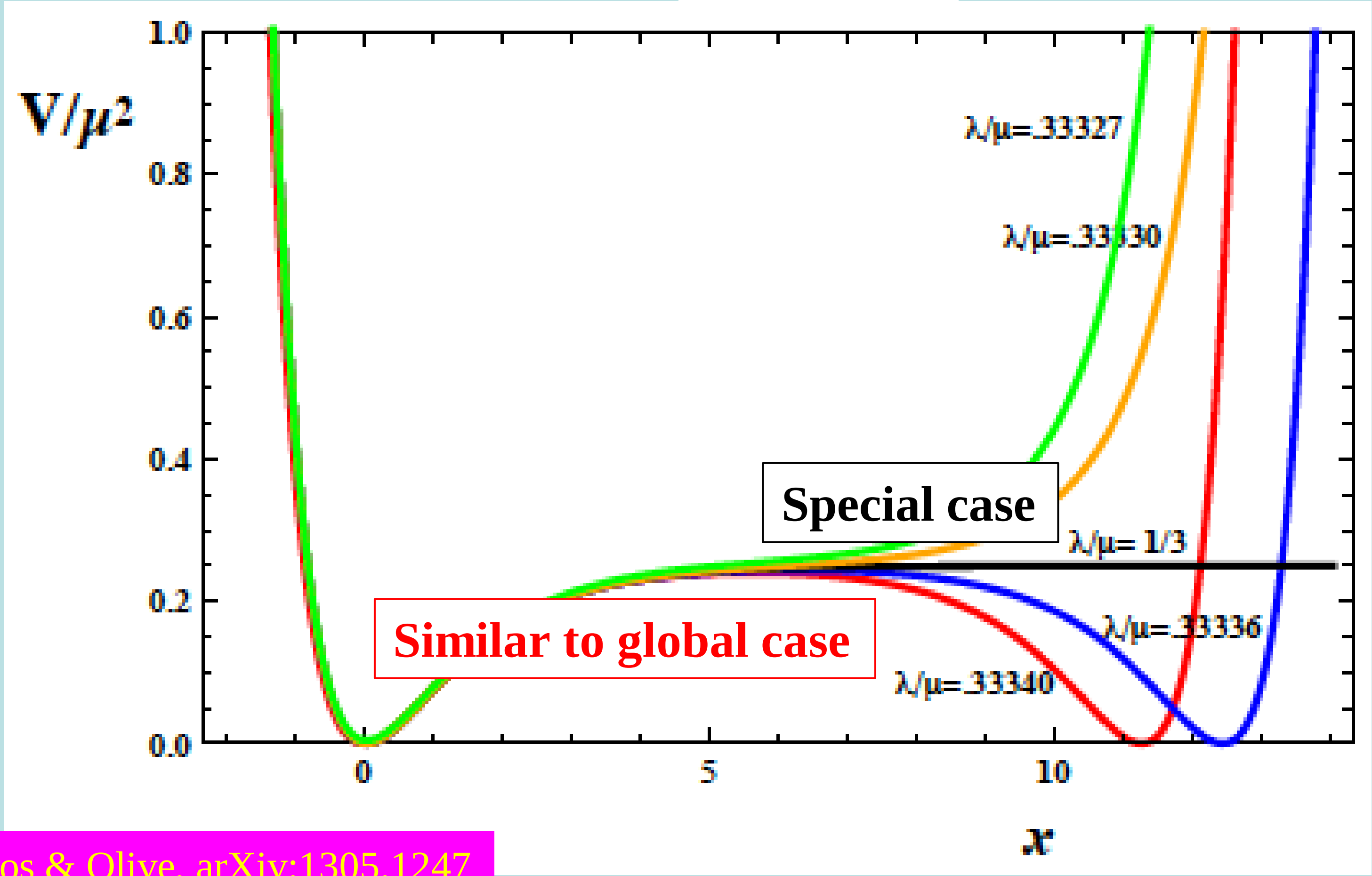
$$\mathcal{L}_{eff} = \frac{1}{2}\sec^2(\sqrt{2/3}y)\left((\partial_\mu x)^2 + (\partial_\mu y)^2\right) -$$
$$\mu^2\frac{e^{-\sqrt{2/3}x}}{2}\sec^2(\sqrt{2/3}y)\left(\cosh\sqrt{2/3}x) - \cos\sqrt{2/3}y\right)^2$$

- Dynamics prefers y = 0: $V = \mu^2 e^{-\sqrt{2/3}x}\sinh^2(x/\sqrt{6})$

JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Supergravity Inflation

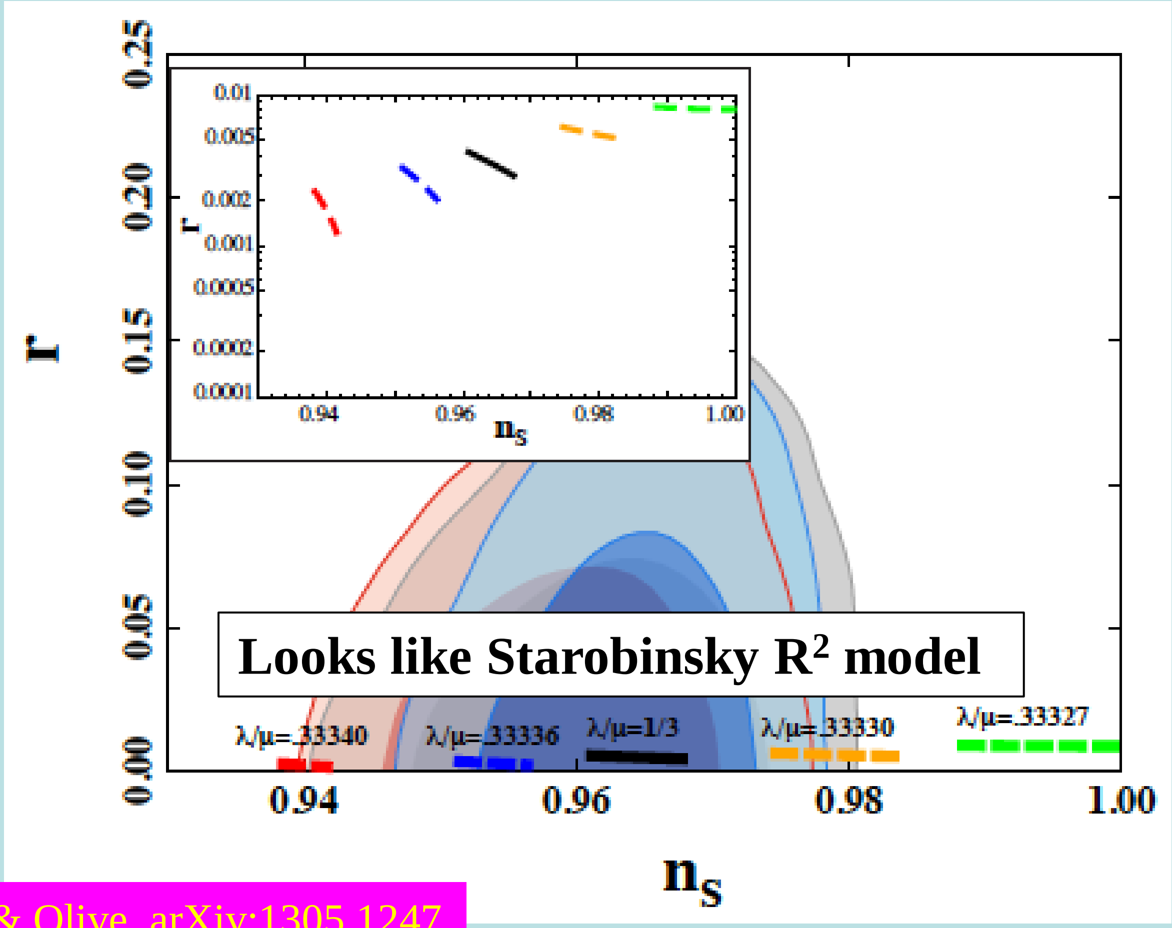
- Inflationary potential for $\lambda \simeq \mu/3$



JE, Nanopoulos & Olive, arXiv:1305.1247

No-Scale Supergravity Inflation

- Good inflation for $\lambda \simeq \mu/3$



JE, Nanopoulos & Olive, arXiv:1305.1247

Is there some profound connection?

- Starobinsky model:

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- After conformal transformation:

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

- Effective potential: $V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$
- Identical with the no-scale Wess-Zumino model for the case $\lambda = \mu/3$

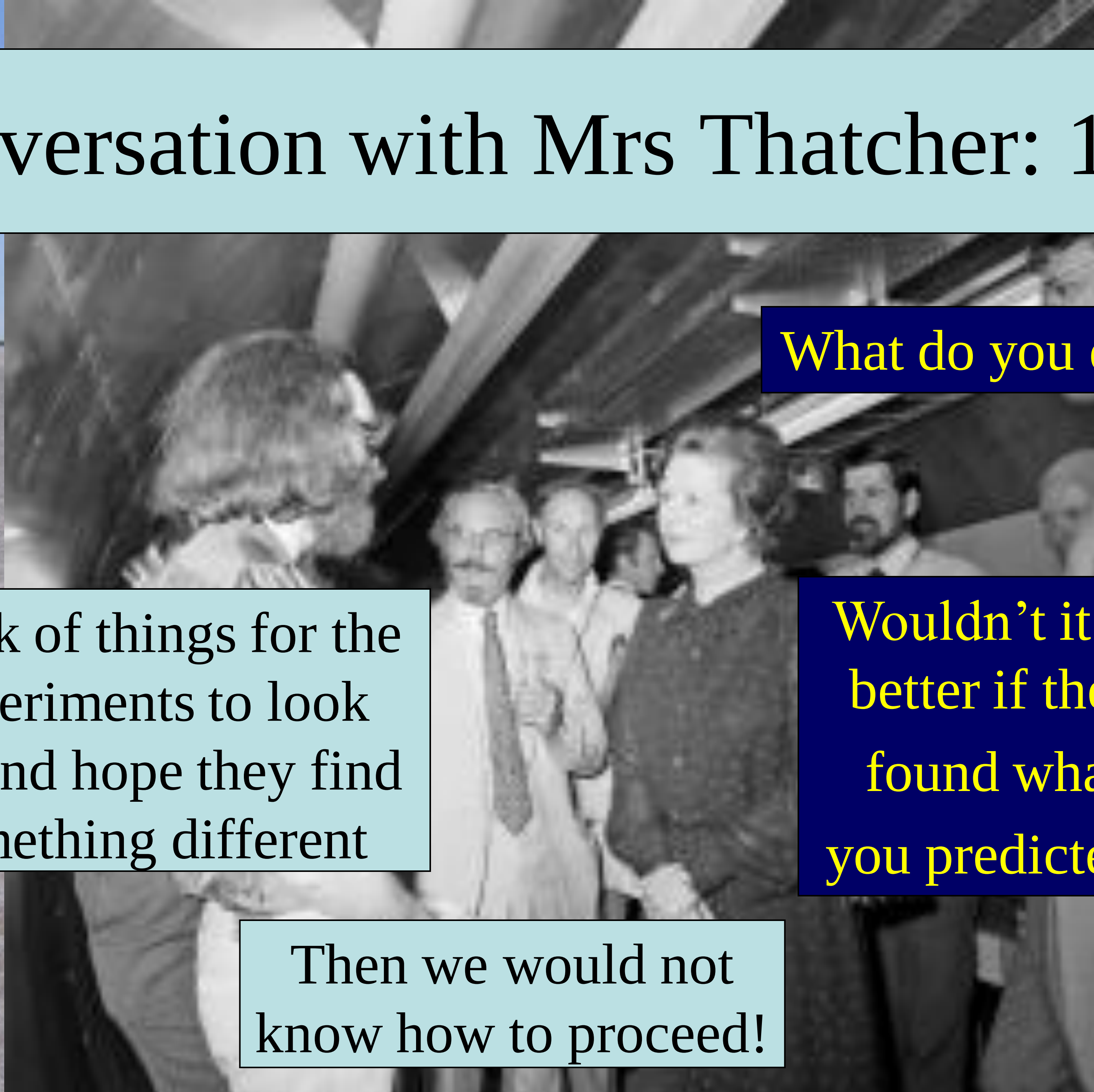
… it actually IS Starobinsky

JE, Nanopoulos & Olive, arXiv:1305.1247

Summary

- The dawn of the scalar era:
  - A Higgs boson at the LHC
  - A cosmological inflaton (?)
- Both would welcome supersymmetry
  - Hierarchy, mass and couplings of Higgs
  - Planck ☺ Wess-Zumino inflationary model
- It seems that we must learn to live with (fairly) elementary scalar fields
- **Can supersymmetry be far behind?**

Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn’t it be better if they found what you predicted?

Then we would not know how to proceed!

Basic Inflationary Formulae

- Strength of perturbations:

$$\left(\frac{V}{\epsilon}\right)^{\frac{1}{4}} = 0.0275 \times M_{Pl}$$

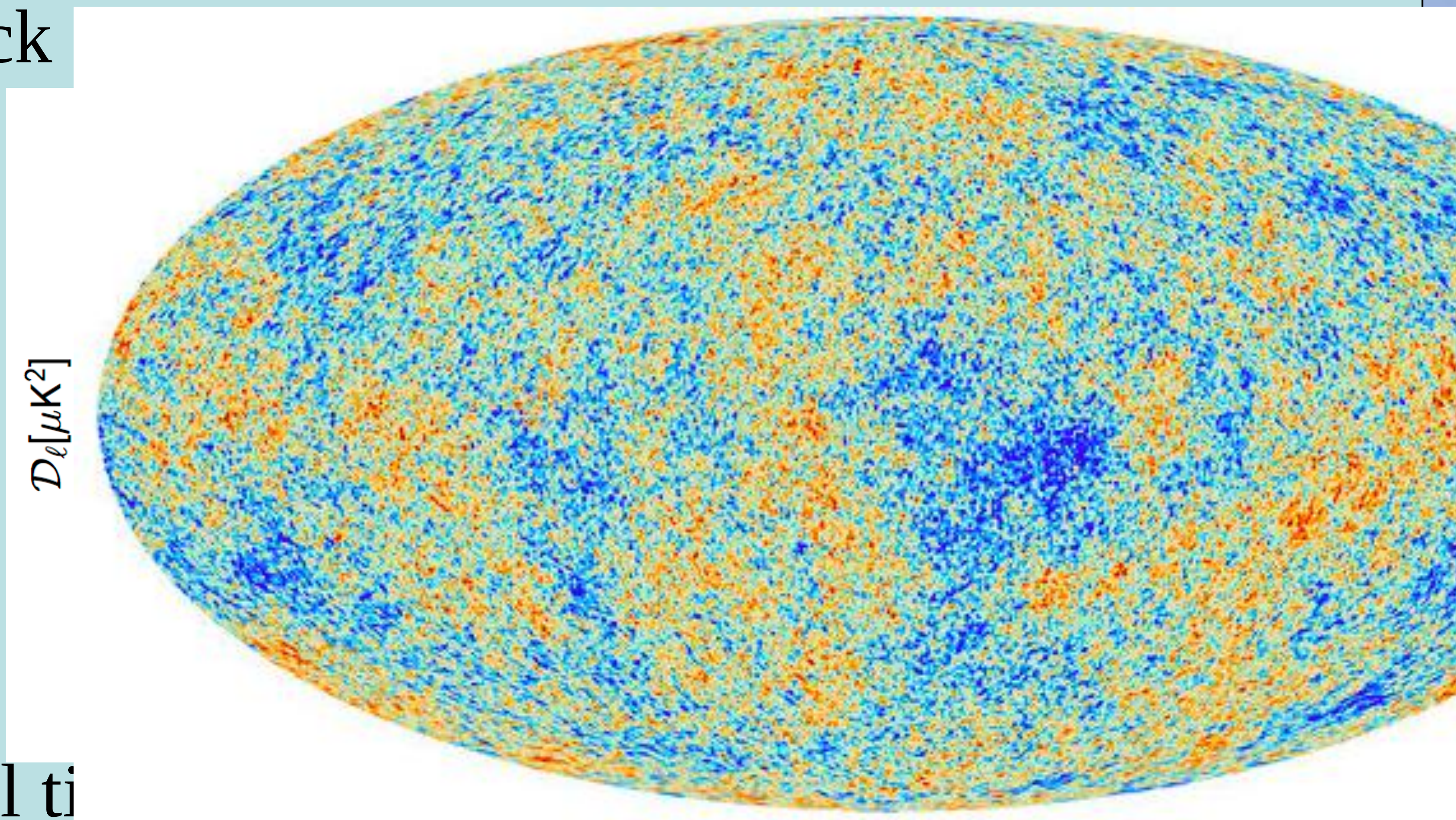
- Slow-roll parameters:

$$\epsilon = \frac{1}{2} M_{Pl}^2 \left(\frac{V'}{V}\right)^2 \quad \eta = M_{Pl}^2 \left(\frac{V''}{V}\right) \quad \xi = M_{Pl}^4 \left(\frac{V'V'''}{V^2}\right)$$

- Tilt of scalar perturbations: $n_s = 1 - 6\epsilon + 2\eta$
- Tensor-to-scalar ratio: $r = 16\epsilon$
- Number of e-folds: $N = \frac{v^2}{M_{Pl}^2} \int_{x_i}^{x_e} \left(\frac{V}{V'}\right) dx$

Cosmological Inflation in Light of Planck

- Planck



- Small ti
- No hint of non-Gaussianity, strings …

The Seminal Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTE

BROKEN SYMMETRIES AND THE MASSES OF GAU

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh,
(Received 31 August 1964)

The only one
who mentioned a
massive scalar boson

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The Higgs Boson

- **Higgs pointed out a massive scalar boson**

$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

- *"... an essential feature of [this] type of theory ... is the prediction of incomplete multiplets of vector and scalar bosons"*
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence
- **Discussed in detail by Higgs in 1966 paper**

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

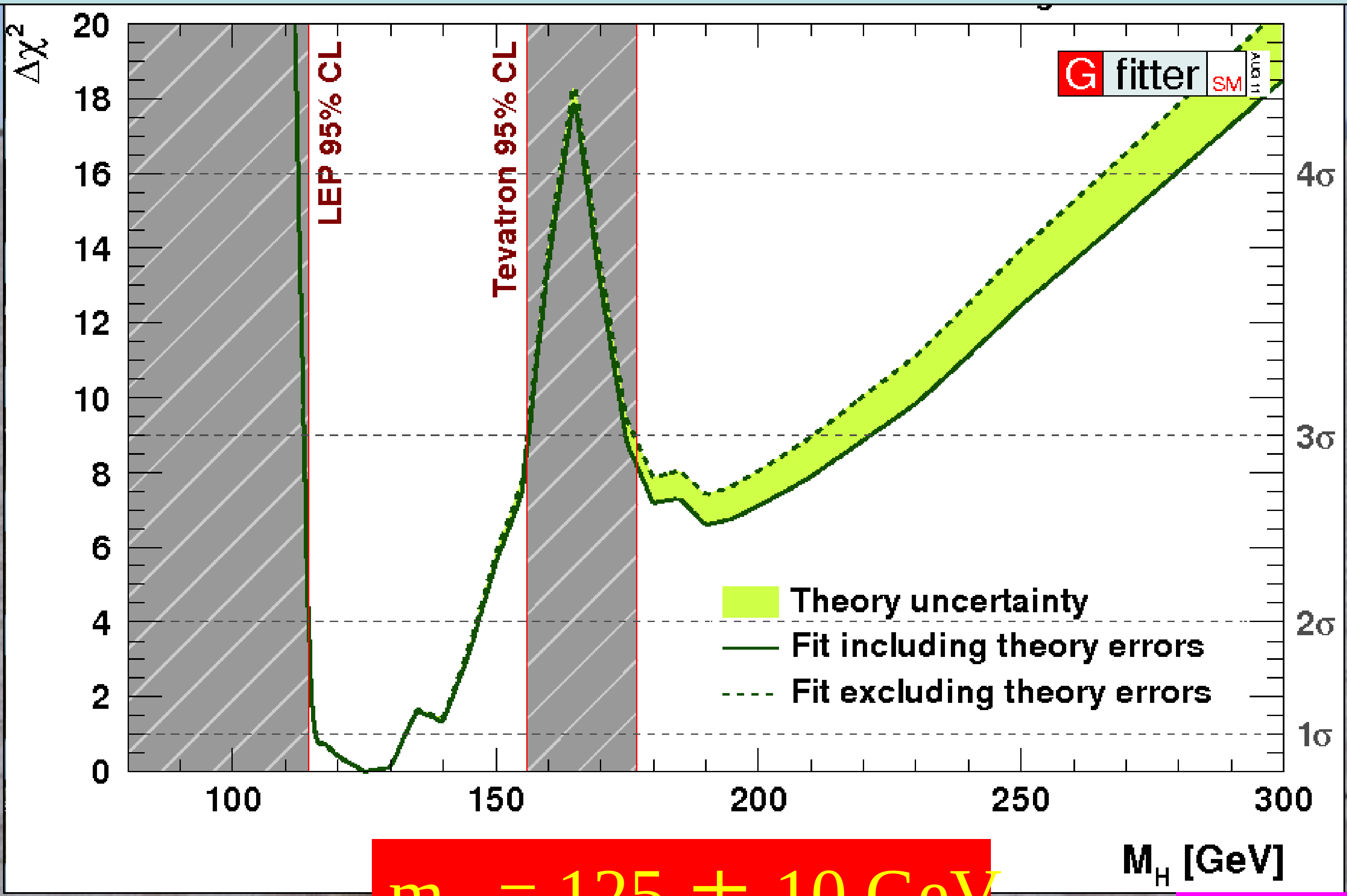
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

2011: Combining Information from Previous Direct Searches and Indirect Data



$m_H = 125 \pm 10$ GeV

Gfitter collaboration